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A comparison of solar photovoltaics and molten carbonate fuel cells as commercial power plants

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ABSTRACT

In line with the worldwide trend, Korea has recognized the importance of renewable energy and extensively supported its exploitation. As of August 2009, the largest incentives for renewable energy are offered to solar photovoltaic (PV) systems, which have vastly increased the installations of this system. On the basis of total paid incentives, the second largest beneficiary is the fuel cell (FC) system. This support has contributed to the successful commercialization of the molten carbonate FC (MCFC) as a distributed generation system (DG). Considering the status of energy systems in Korea, solar PV and MCFC systems are likely to be further developed in the country.

The present paper analyzes the exploitation of these two energy systems by conducting a feasibility study and a technology assessment in the Korea environment based on many assumptions, conditions and data involved. The feasibility study demonstrates the positive economic gains of the solar PV and MCFC power plants. The unit electricity generation cost of solar PV is twice that of an MCFC system. In addition, the study reveals the slightly greater profitability of the MCFC. Exact estimation of their future economies is impossible because of uncertainties in many future conditions and environments. Nevertheless, the development of solar cells with higher efficiency is undoubtedly the most critical factor in increasing future profits. On the other hand, reductions in the operation and maintenance (O&M) costs and the natural gas (NG) price are the most important issues in raising the viability of the MCFC system.

Contents

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1. Introduction

One of the most important issues in the world is climate change due to excessive emissions of greenhouse gases (GHGs). The exploitation of new, renewable and sustainable energy may be the most effective way to mitigate GHG emissions. Therefore, most nations are trying to exploit these energies.

Except for hydroelectric energy and some bio-fuels, the solar photovoltaic (PV) and wind power are the most commercialized among the renewable energy sources. Others are partially commercialized and remain in the stages of demonstration and R&D. The status of renewable energy and technology differs greatly between countries as each nation exploits its own renewable potential supplies and develops policies according to its energy sources, supply and demand, as well as social and economical environment.

Although the fuel cell (FC) system uses hydrogen (H_2) as the fuel for highly efficient electricity production, it is not considered a renewable energy because H_2 production remains mostly sourced from fossil fuels. However, the FC system has currently received much attention due to its even higher efficiency, utilization, quality of electricity produced and system stability compared to the other renewable energies. In addition, the system will be considered another renewable energy source when H_2 production without any GHG emissions achieves commercial viability in the near future. While the practical application of FCs for residence and transportation application field will require more research, the molten carbonate FC (MCFC) system with MW-scale power generator for distributed generation system (DG) has already begun commercialization and is offering the same benefits as those of renewable energies to the country. For example, Korea currently offers various benefits such as financial incentives, loans and tax reductions to FC systems with the same conditions as those for renewable energy [1]. These supporting policies will advance the successful commercialization of MCFC and contribute to the development of the FC as a commercial power plant [2,3].

Solar PV and MCFC systems share many similar, but also different, aspects. The most significant difference is the energy source: unlimitedly exploitable clean solar energy vs. H_2 from fossil fuels. Because of this fundamental difference in the resources, the two systems exhibit their own unique features. The main difference is the environmental friendliness (without emissions) or unfriendliness (with emissions). Another difference is the intermittence of the power generation, which induces a wide divergence in system utilization: very low for solar PV and very high for MCFCs. Therefore, solar PV is generally used as a power supply with restrictions, whereas FC systems can be used as constant and regular power sources with higher and more stable quality.

The two systems also share many common points. There are few constraints on the plant site condition. Unlike other renewable energy systems, they can be constructed anywhere such as near the consumer or in remote local areas, as well as locations providing easy connection to the power grid system. Therefore, both systems can be employed as the most efficient DG system.

Their other common feature is the installed capacity range available for commercial DG. While the two systems can be installed with various scales, many solar PV power plants have been installed with a capacity under 3 MW. The capacity of most of the MCFC power plants currently operated in Korea is around 2.4 MW, due to technology restrictions, the readiness of operation and maintenance (O&M), and the economy. However, the capacity of solar PV plants can easily be extended by bundling up modules or arrays. For FCs, the maximum capacity of the unit MCFC system (module) for commercial purpose is currently 2.4 MW [4]. Therefore, the two systems could be competitive or supplementary in the field of DG systems.

Korea, like other nations, has recognized the importance of renewable energy and extensively supported its exploitation. The total incentives paid to the renewable energy sources (except for hydro power) under the feed-in-tariff (FIT) program over the last five years are shown in Fig. 1.

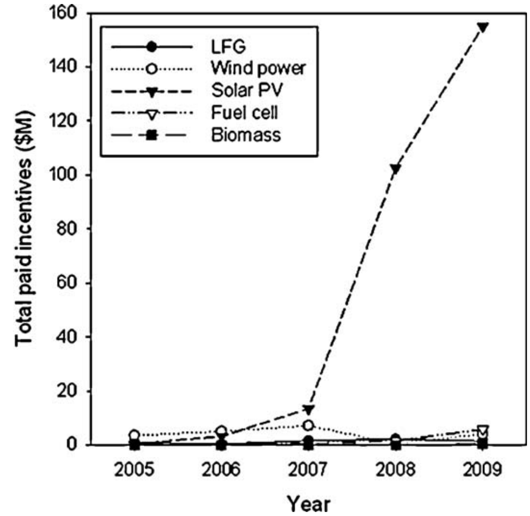

Fig. 1. Total incentives paid to renewable energy by the FIT program in Korea.

As of August 2009, US$155 M was provided as incentives to the owners of solar PV power generation plants, which is 92% of the total incentives paid to all renewable energy sources. The second beneficiary was not wind turbine but FCs. While the power generated by wind turbines, 285.45 GWh, was larger than that produced by FCs, 35.95 GWh, the incentives paid to FCs, $5.7 M, were larger than those to wind power, $4 M [1,5]. In addition, the grid connecting MCFC systems using natural gas (NG) as the fuel for power and heat generation obtained approval from the UN as a clean development mechanism (CDM) methodology in July 2009 [6]. Therefore, CDM credits and a request for emission rights were granted to the MCFC-based DG systems using NG. Therefore, considering the status of these two energy systems, the solar PV and MCFC systems are confidently expected to undergo further development in Korea.

The present study analyzes the exploitation of these two energy systems, including their status, and assesses their technology by conducting a feasibility study and examining their competitiveness in the Korea environment. Many assumptions, conditions and data, including system performance and economy, are employed for the analysis. Most of them are based on real values from solar PV and MCFC power plants currently operated in Korea. Therefore, it is hoped that this paper will provide useful information to efficiently exploit the two energy systems and contribute to system improvement.

2. Status of renewable energy in Korea

No universally recognized definition of renewable energy has been agreed upon and its meaning differs slightly among countries and their statistics and related data reported are non-uniform. Nevertheless, the definition and data of the International Energy Agency (IEA) are the most widely used as standards. Many IEA members report their energy statistics based on the IEA standard. IEA classifies renewable energy into hydro power, geothermal energy, solar energy, wind energy, ocean energy (tide and wave), solid biomass, charcoal, bio-gas, liquid bio-fuels and renewable municipal waste.

In Korea, however, the term New and Renewable Energy is formally used instead of renewable energy. This term was defined in the Promotion Act for the Exploitation and Dissemination of the New and Renewable Energy by revising the related law in 2005. According to the Act [7], the New Energy is defined as the newly

Table 1
Amount of energy generated by renewable sources between 2001 and 2008 in Korea (kTOE) [1].

	2001	2002	2003	2004	2005	2006	2007	2008
Solar thermal	37.1	34.8	32.9	36.1	34.7	33.0	29.4	28.0
Solar PV	1.5	1.8	1.9	2.5	3.6	7.8	15.3	61.1
Biomass energy	82.5	116.8	131.1	135.0	181.3	274.5	370.2	426.8
Wastes energy	2,308.0	2,732.5	3,039.3	3,313.2	3,705.5	3,975.3	4,319.3	4,568.6
Hydro power	20.9	27.6	1,225.6	1,082.3	918.5	867.1	780.9	660.1
Wind power	3.1	3.7	5.2	11.9	32.5	59.7	80.8	93.7
Geothermal energy	0	0.1	0.4	1.4	2.6	6.2	11.1	15.7
Fuel cells	0	0	0	0	0.5	1.7	1.8	4.4
Total (kTOE)	2,453.1	2,917.3	4,436.4	4,582.4	4,879.2	5,225.3	5,608.8	5,858.5
% of total nation's energy generated	1.5	1.8	2.1	2.1	2.1	2.2	2.4	2.4

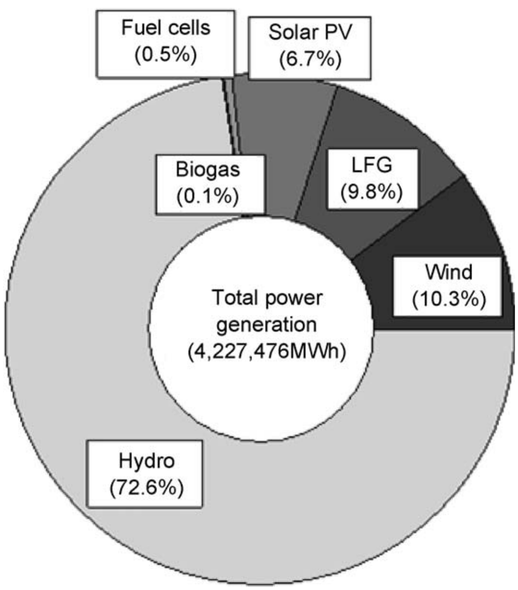

Fig. 2. Total electricity generated by renewable energy sources and their proportions in 2008.

exploitable energy converting fossil fuels, including FCs, integrated gasification combined cycle (IGCC) and H_2 energy. Meanwhile, the Renewable Energy is divided into eight categories: solar PV, solar thermal, biomass, wind power, hydro power, ocean, wastes and geothermal energy. These 11 energy categories are currently and officially named as the New and Renewable Energy and have benefited equally from the various supporting polices. In this paper hereafter, the term renewable energy describes these categories of the New and Renewable Energy used in Korea.

Among the 11 renewable resources, eight contribute practical amounts to the nation's energy production, as listed in Table 1.

In 2008, the total energy produced by the first energy resources was approximately 241 MTOE. The total energy generated by the eight renewable sources was about 5.9 MTOE, which was only about 2.4% of the total energy produced [5,8,9]. In addition, the six energy sources generated approximately 4227 GWh of commercially available electricity, and the shares are shown in Fig. 2 [8].

While the total installed capacity of renewable energy was about 3% of the total installed capacity of all power plants in the country, the total electricity produced by renewable energy was only about 1% of the total nation's electricity production, i.e., the current average utilization of renewable energy is only one third of that of traditional power plants. Solar PV and wind power contributed 17% of the total electricity produced by renewable sources, but the contribution of FCs was negligible at 0.5%.

There is a long-term plan to increase the portion of renewable energy to 9% of the total energy produced in Korea by 2030 [9]. The government expects the plan to be achieved by intensive supporting of R&D on renewable energy, with a particular focus on five selected resources: solar PV, wind turbine, FCs, IGCC and bio energy.

2.1. Grid parity

The nation's grid parity is very useful information to directly compare to the competitiveness of renewable energy in terms of the economy. The nation's grid parity, as of 2008, is summarized in Table 2.

Firstly, these are based on the current portion of the power sources to the total nation's power generated. The data in the third column and 62.6 $/MWh are the currently accepted production cost and the grid parity reported by the Korea Power Exchange, respectively [10]. However, these values were calculated without considering the additional cost due to the CO_2 penalty of the fossil fuels. Therefore, a new grid parity considering the CO_2 emission factor of fossil fuels is required to compare the relative electricity production cost of renewable energy. International Atomic Energy Agency (IAEA) – or Intergovernmental Panel on Climate Change (IPCC)-based emission factors could be applied to the estimation, except for the hydro and nuclear energy. IAEA factors are based on the direct amount of CO_2 emissions of the fuels used solely for

Table 2
Current grid parity including unit power generation cost of traditional energies and their compositions, as well as grid parity considering the CO_2 emission penalty.

Traditional power sources	Composition (%)	Power generation cost without considering CO_2 emissions ($/MWh)	Additional cost due to CO_2 emission ($/MWh)	
			Based on IAEA	Based on IPCC
Hydro	1.3	124.3	–	–
Coal (bituminous)	40.7	46.5	30.6	30
Petroleum (heavy fuel oil)	4.1	173.5	24.2	24.79
NG	17.1	130.6	17.0	18.05
Nuclear	35.6	35.5	–	–
Grid parity ($/MWh)		62.6	79	78.9

Table 3
Installed capacity and power generated by solar PV and FC systems [8].

		2004	2005	2006	2007	2008	October 2009
Solar PV							
Installed capacity (MW)	Commercial	0.238	1.224	9.071	28.842	259.110	49.414
	Residential	2.315	3.766	13.251	16.505	16.555	–
	Sub total	2.553	4.990	22.322	45.347	275.665	–
Power generated (MWh)	Commercial	13	595	5,666	25,722	216,314	–
	Residential	9,859	13,804	25,356	45,557	68,002	–
	Sub total	9,872	14,399	31,022	71,279	284,315	–
Fuel cells							
Installed capacity (MW)	Commercial (MCFC)	0	0	0.250	0	7.800	14.400
	Residential (PEMFC)	0	0.756	0.020	0.025	0.051	–
	Sub total	0	0.756	0.270	0.025	7.851	–
Power generated (MWh)	Commercial	0	0	311	1,960	13,432	–
	Residential	0	2,103	6,370	6,562	6,878	–
	Sub total	0	2,103	6,681	8,522	20,310	–

power generation, whereas the IPCC data are given as the total emissions from fuel combustion. The efficiency of fossil fuel-based power plants is assumed to be 34.4% in Korea. Despite the two different options, the grid parity was estimated to be about 79 $/MWh as listed in Table 2. This value shows the significant effect of the CO_2 penalty, which increased the current grid parity by 25%. Furthermore, this is the standard basis to quantitatively compare the economy of renewable energy.

2.2. Support for the exploitation of renewable energy

Currently, many supporting systems for exploiting renewable energy, such as incentives, financing, loans and tax reductions are being extensively offered in Korea. Among them, the incentives offered by the FIT program and the low interest loans are believed to be the most effective for developing renewable energy. The incentives have been given to six renewable energy sources in the last seven years: hydro, landfill gas, solar PV, FCs and biomass. In fact, the FIT program has substantially contributed to the development and dissemination of renewable energy, as is detailed in the next section. Meanwhile, the renewable portfolio system (RPS) is scheduled to begin in 2012.

3. Solar PV and FC system

3.1. Installed capacity and power generated

Solar PV power plants began to be installed in the late 1990s. Many small plants for residential use were constructed between 2000 and 2006. Commercial plants with capacities of hundreds of kW and MW have been extensively constructed since 2007. The installed capacity in 2008 was estimated to be 259 MW [1], as listed in Table 3. However, the capacity in 2009 decreased rapidly due to reduced incentives and plant cost increases.

As of October 2009, approximately 1215 solar PV power plants were operated throughout the nation with capacity ranging from 3 kW to 24 MW. The total installed capacity was 347 MW and incentives were offered for this capacity. The total power generated was 284 GWh in 2008 [1], which was 6.7% of the total power generated by renewable energy, as shown in Fig. 2.

Because the annual insolation and ambient temperature do not vary greatly across the nation, there are few restrictions in terms of environment condition on the suitable sites for solar PV power plants. However, the land price varies greatly between urban and rural areas and the city cost index is very high. Therefore, many large plants have been constructed in rural areas, particularly in the wasted salt field of the Yellow Sea and west-southern sea of the peninsula. Environmental considerations have also impacted the locations.

Meanwhile, the installation of FC systems for residential use was earnestly begun in 2005. The system was based on proton exchange membrane FC (PEMFC) with a capacity of 1 kW and the system has been monitored for three years. However, the system has not been widely used, as listed in Table 3. On the other hand, the installed capacity of MCFC power plants for commercial use was sharply increased to about 23 MW in the last two years. Currently, 11 power plants have been installed and are operating, as listed in Table 4 [11–13].

Three plants are public electricity utilities and the others are commercial companies. Most of them use NG directly supplied from the city gas grid as the fuel. They are uniformly dispersed throughout the country, including Seoul and Pohang. However, they were constructed at the sites with various environmental conditions such as in a traditional NG power plant, paper

Table 4
MCFC-based fuel cell power plants currently operating in Korea.

No.	Owners	Power capacity (MW)	Location	Operation starting date
1[a]	Korea South-East Power Co.	0.25	Bundang	November 2006
2	POSCON	0.3	Pohang	March 2008
3	POSCO-Power	2.4	Pohang	August 2008
4	HS-EPA Co.	2.4	Jounju	October 2008
5	Naturapower Co.	2.4	Gunsan	September 2008
6[a]	Korea Midland Power Co.	0.3	Boryeong	September 2008
7	Nowon CHP	2.4	Seoul	May 2009
8	GS-EPS Co.[b]	2.4	Dangjin	September 2009
9	MPC Youlchon	4.8	Yeosu	September 2009
10[a]	Korea East-West Power Co.	2.4	Ilsan	September 2009
11	POSCO-Power	2.4	Incheon	October 2009

[a] Public electricity utilities.
[b] Electricity efficiency is 47% and the overall efficiency is 67% based on CHP.

Table 5
Characteristics of the FIT program and the benefits offered to solar PV and MCFC systems.

	2007	2008	August 2009	2010	2011
Solar PV					
Limiting capacity applicable to FIT (MW)	–	300	50	70	80
Unit incentives[a] ($/kWh)	0.616	0.510	0.510	0.441	Not assigned
Power generated (MWh)	24,036	206,018	300,618	–	–
Total paid incentives by FIT ($M)	13.429	102.588	155.021	–	–
Fuel cells					
Limiting capacity applicable to FIT (MW)	–	8	12	14	16
Unit incentives[b] ($/kWh)	0.257	0.249	0.242	0.234	0.227
Power generated (MWh)	1,960	12,218	35,945	–	–
Total paid incentives by FIT ($M)	0.357	1.505	5.655	–	–

[a] Applicable to a capacity of 1–3 MW for a 15-year crediting period, irrespective of the site condition.
[b] Available for traditional NG gas.

manufacturing plant, science park, and municipal solid waste incinerator plant. These locations were chosen to increase the synergy effect of the traditional process such as NG supply, power grid and heat management.

3.2. FIT and incentives

As mentioned before, incentives have been offered through the FIT program to six renewable energy generators with a total power generation in 2009 of approximately 1185 GWh, which equates to $107 M of incentives [1]. Among them, the incentives paid to solar PV and FC systems are summarized in Table 5.

The FIT program offers incentives only up to the limitation of installed capacity due to the RPS enforcement scheduled in 2012. The limits for renewable energy have already been set at 500 MW and 50 MW for solar PV and FCs, respectively, of which 350 MW and 20 MW have been used and the remainder will be allotted in the next two years. The incentives are guaranteed to be paid for 15 years within the limiting capacity.

The incentives paid to solar PV in 2009 were 94% of the total incentives offered to all renewable energy. The incentives given to FCs in 2009 increased with the fastest growth rate of 4-fold more than that in 2008. Furthermore, the absolute amount of incentives paid in 2009 was 40% larger than that of wind turbine. However, the 36 GWh of power generated by FC is only about 12.3% of that by wind power, as listed in Table 5. This was ascribed to the high expense of the FC system with a unit incentive price even higher than that of wind power.

The unit incentive price of solar PV is about double that of FCs at traditional conditions, as shown in Table 5. In fact, however, the unit incentive price of the two energy systems differs slightly according to the case. For solar PV, it depends on the installed power capacity and the crediting period of the FIT program. For FCs, it is slightly influenced by the fuel sources such as NG or bio-methane. In addition, the unit incentive price of solar PV and FCs has been reduced at annual rates of 13.5% and 3% on average, respectively. This decrease is mostly due to the cost reduction according to the system development. However, the system marginal price (SMP), which is another key factor to determine the unit incentive price, is continuously raised every year, from 0.076 $/kWh in 2007 to 0.111 $/kWh in 2008, in contrast to the drop in unit incentive price. Therefore, the difference between the unit incentive price and SMP is constantly increasing. Nevertheless, the impact of SMP on the unit incentive price may be negligible because the SMP is determined primarily based on the traditional power system and the current portion of renewable energy is very slight. However, this situation is unlikely to be unchanged during the next 15 years. Therefore, it is impossible to predict the exact future variation of the unit incentive price.

4. Feasibility study on solar PV and MCFC systems

The feasibility study on the two systems was carried out based on various assumptions and conditions, as well as the data involved. For these studies, firstly, the features of the three representative power plants of each system currently operating were previewed, as listed in Tables 6 and 7. These include data officially announced by owners, such as power capacity and plant cost, as well as the values calculated by the author based on the given data.

Solar PV power plants have recently been constructed for commercial purposes and Plant 1 is the largest facility in Korea. While all the plants are bigger than 10 MW, they have been gradually increased by the addition of individual systems with capacities of 2–3 MW. The total plant costs were reported to be 177 $M, 127 $M and 100 $M for Plants 1, 2, and 3, respectively [14–16]. Therefore, the plant cost per MW was calculated as 7.2 $M on average, which is similar to the value generally accepted in Korea as the standard plant cost of solar PV in 2008, excluding financial costs. This value was assumed for the feasibility study.

Plant 1 is located in a wasted salt field in the southwest region of the peninsula which traditionally has the highest average insolation. Plant 2 was constructed in the cut foot of an inland mountain and Plant 3 in a wasted salt field in the Yellow Sea. The tracking system is known to exhibit a 15% higher utilization than the fixed system. Nevertheless, the 16.6% utilization of Plant 1 was more or less conservative. The average utilization of the three

Table 6
Features of three representative solar PV power plants.

No.	Owners (location) (completion data)	Power capacity (MW)	Plant cost per MW ($M/MW)	Power generated (MWh)	Utilization (%)	CO_2 avoidance (tCO_2/MWh)	Plant area (m^2/MW)	Comment
1	Tongyang E&C Co. (Shinan) (November 2008)	24	7.4	35,000	16.6	0.7143	27,917	One-axis tracking 130,656 modules
2	Samsung Everland Co. (Gimcheon) (September 2008)	18	6.9	26,000	16.1	0.6538	31.522	One-axis fixed 87,000 modules
3	LG Solar Co. (Taean) (June 2008)	14	7.1	19,000	15.5	0.6316	21,429	One-axis fixed 78,000 modules
	Average		7.2	26,667	16.1	0.6666	26,956	

Table 7
Features of three representative MCFC power plants.

No.	Owners	Power capacity (MW)	Total plant cost ($M)	Plant cost per MW ($M/MW)	Power generated (MWh)	Utilization (%)	Comment
1	HS-EPA Co.	2.4	10.9	4.5	19,552	93	FC; DFC 3000
2	Naturapower Co.	2.4	13.6	5.7	19,000	90.4	FC; Two DFC1500MA Plant area; 3330 m^2
3	POSCO-Power	2.4	12.7	5.3	17,000	80.9	DFC 3000 Construction period; seven months Potential emission reduction; 2500 tCO_2/yr
	Average		12.4	5.2	18,517	88.1	

plants was calculated as approximately 16.1%, and this value was assumed for the feasibility study. The CO_2 avoidance and plant area were calculated based on officially reported data by the owners. The plant area is the total area, including all facilities and spaces.

The total capacity of the selected MCFC power plants was 2.4 MW, as listed in Table 7. They were commercially constructed with a total plant cost of 12.4 $M on average, which equates to 5.2 $M per MW. This is 28% less than that of solar PV systems. The annual power generated by one plant was estimated to be 18,517 MWh, with an average utilization of 88%. The system supplier claims a stack lifespan of about three years. The comments in the table are based on the owner's report. Their sites and conditions are summarized in Table 4.

4.1. Assumptions

The assumptions and conditions for the feasibility study are summarized in Table 8.

The system capacity was assumed to be 2.4 MW for each system, considering the aforementioned current situation. In fact, the capacity of most MCFC power plants is 2.4 MW and many commercial solar PV plants are operated with capacities between 1 MW and 3 MW. The efficiency of the solar cell was assumed to be 12%, which is the most widely accepted value for the crystalline silicon wafer-based solar PV system, which is currently the most advanced. On the other hand, the efficiency of MCFC plants was assumed based on the data reported by the system suppliers. However, the assumed efficiencies of the two systems were based on the DC power generated without considering the loss due to AC conversion. This absence may have exaggerated the system benefit. The efficiency of 12% for solar PV is the only available figure for standard conditions of module temperature and illumination. Therefore, 10–20% of the efficiency is lost in real environments. Other factors decreasing the rating in solar PV include packing-factor loss, electrical losses due to module-mismatch and field wiring resistance. In addition, the conversion efficiency of the inverter is less than 100%. Considering all these losses, the sum of AC available for real use is approximately 70% of the DC ratings of the module produced. Furthermore, the thermal degradation of the solar cell according to lifetime must be considered.

While the stand alone MCFC system efficiency is slightly different from the system details, the system supplier claims an efficiency of 47% [4,17,18]. This is likely to be the maximum value that may not be attainable in real plants.

Meanwhile, it is possible to systematically apply the similar restrictions of the solar PV to the efficiency of MCFC. In addition, many technological problems that remain unsolved have the potential to decrease the efficiency such as dissolution of the NiO-based cathode, anode poisoning, resistance due to stacks, and corrosion of the housing. However, none of these losses has yet been quantitatively and clearly reported, unlike the solar PV system. Considering these factors, the efficiency of the MCFC system should be assumed to be less than 47%.

However, the feasibility study was based on comparative analysis and the most of the aforementioned factors capable of reducing the available energy may be substantially overcome in the near future. Therefore, the efficiencies of the solar PV and MCFC were assumed to be 12% and 47%, respectively.

MCFC utilization is known to be relatively very constant, at about 90%. However, the average utilization for the feasibility

Table 8
Various assumptions, conditions and data required for the feasibility study.

	Solar PV		Fuel cells	
Plant size (MW)	2.4		2.4	
Efficiency[a] (%)	12		47	
System utilization	16.1		88.1	
Plant cost per MW ($M/MW)	7.2		5.2	
Financing	Commercial loan, 4.5% of yearly interest			
Redeem	Equally year repayment for 15 years			
O&M cost (% of plant cost including interest)	1		10	
Fuel	0		100% CH_4 gas, 13 $/mmbtu	
Unit incentive price ($/kWh)	0.510		0.249	
CDM methodology	ACM0002		AMS-III.AC	
	Operating margin (tCO_2/MWh)	0.7448	Operating margin (tCO_2/MWh)	0.5490[b]
	Build margin (tCO_2/MWh)	0.6520	Build margin (tCO_2/MWh)	0.6520
	Baseline emission factor (tCO_2/MWh)	0.6984	Baseline emission factor (tCO_2/MWh)	0.6005
	Project activity emissions (tCO_2/MWh)	0	Project activity emissions (tCO_2/MWh)	0.4070[c]
Price of CERs	20 Euro/tCO_2 (Based on 2008)			
Exchange rate	1100 KRW/US$ (based on 2008)			
Total plant area	3-fold of array area		3-fold of fuel cell system area (including BOP)	

[a] The conversion ratio of resource to electricity (DC).
[b] The IPCC emission factor.
[c] Data from Poscopower.

study was based on the representing plants. The plant cost was also assumed based on the representing plants and financing was based on the commercial loan conditions which were offered in 2008. The O&M cost of MCFC was assumed to be even more than that of solar PV [10], for reasons described in the next section. The NG price was based on the average spot price and the unit incentive price was based on the 2008 value in Korea.

The CDM methodologies of ACM0002 [19] were applied to calculate the CER credit in the solar PV system. The operating and build margins (OM and BM) were based on recent domestic data [8]. The baseline emission factor was calculated according to the equation 0.5OM + 0.5BM. The CO_2 emission during the project activity of the solar PV was neglected.

To calculate the obtainable CER credits for the MCFC system, the methodology of the AMS-III.AC guideline for electricity and/or heat generation using FCs [20] should be applied. The procedure to calculate the emission factor is very similar to that of solar PV, excluding the OM value. Among four scenarios for baseline calculation, because the MCFC fuel was only NG, the IPCC emission factor of NG was directly employed as the OM, instead of the nation's three-year averaged emission factor. However, many of the data that are required to calculate the other value using this methodology have not yet been determined. The most representative datum is the additional steam or heat generation by FCs. Although the system supplier claims that it approached about 20% of NG's theoretical energy, this value requires monitoring and confirmation in a real setting. The leakage, which is essential to calculating the system emissions, has also not been clearly reported. This includes fugitive CH_4 emissions, CO_2 emissions from associated fuel combustion and flaring. Therefore, these factors were neglected in the present study. However, the substantial emission of CO_2 from CH_4 reforming in the H_2 production process must be considered. This emission was assumed to be 0.407 tCO_2/MWh, as reported by the system supplier [2].

4.2. Results

Based on the 2008 data, the results of feasibility study are summarized in Table 9.

Firstly, the total plant cost was $22.9 M and $16.6 M for solar PV and MCFC, respectively. For solar PV, this consisted of total equipment cost (PV cells, PV modules, trackers, power conditioning unit, and BOP), general facilities and engineering fee, project and process contingency, and financial cost. For a plant lifetime of 15 years, the annual plant cost was $1.53 M. Adding the O&M cost to the plant cost, the total cost invested in 2008 was estimated to be $1.76 M.

For the MCFC system, the equipment was FCs with stack, reformer, power conditioning and BOP. If the same procedures were applied as the solar PV, the total plant cost was 72.4% of that of solar PV. However, the average annual O&M cost is $1.662 M. Furthermore, a large annual fuel cost was approximately 39% of total cost annually invested. Therefore, the total cost of MCFC was about 2.6-fold more expensive than that of solar PV.

The total revenue is composed of the total paid incentives and the obtainable CER credit. The total incentive offered to the MCFC system was estimated to be 2.7-fold more than that to solar PV. This is primarily ascribed to the total annual power generated by the MCFC with a utilization that is even higher than that of solar PV. The contribution of the CER credits to total revenue for each system was very small compared to the incentives. The results of calculating the CER credits are listed in Table 9 for both energy systems. The larger power generation of the MCFC influenced the higher CER credits. Contrary to expectation, the absolute credit offered to the MCFC system was even more than that of solar PV.

Based on the total cost and revenue, the profits of the two systems and their unit electricity generation cost were estimated. The feasibility study indicated that the solar PV and MCFC power plants offered a positive economy, as listed in Table 9. However, the MCFC was slightly more profitable with a unit electricity generation cost only half that of solar PV. The study also revealed that the calculated site area of solar PV was even larger than that of the MCFC power plant.

5. Discussion and conclusions

The feasibility study demonstrated the positive economy of the commercial solar PV and MCFC systems based on 2008 data. However, it is impossible to exactly estimate their future economies because of many uncertainties in future conditions and environments over the next 15 years. For example, the RPS is scheduled to begin in 2012 in place of the FIT program. The predictable changes include the reduction of incentives, and increased grid parity and NG price. The system technology is clearly expected to be improved in the future. Nevertheless, estimating the extent of all these variables and their effects is almost impossible. It is clear that positive environments will not be created in terms of incentive and credit. Therefore, an ongoing reduction in the total cost is the only viable solution to maintain positive profits and this can be achieved though the development of advanced technologies for the two energy systems.

The nation's grid parity based on CO_2 emission penalties is a critical standard to analyze the economy of the renewable energy system. Therefore, the unit electricity generation cost of solar PV and MCFC should be reduced to one sixth and one third of their estimated cost, respectively. The present and future efforts to achieve these goals are summarized below.

Table 9
Results of the feasibility study on solar PV and MCFC power plants with a capacity of 2.4 MW.

	Solar PV	Fuel cells
Total cost ($M/yr)	1.760	4.517
- Plant cost including interest ($M/yr) (Plant cost + interest (4.5%))	1.53 (1.144 + 0.386)	1.108 (0.828 + 0.280)
- O&M cost ($M/yr)	0.23	1.662
- Fuel cost ($M/yr)	0	1.748
Total revenue ($M/yr)	1.799	4.957
- Total incentives ($M/yr)	1.726 (96%)	4.614 (93%)
Annual power generation (MWh)	3,383	18,517
- Obtainable CER credit ($M/yr)	0.073 (4%)	0.344 (7%)
CO_2 baseline emission (ton/yr)	2,363	11,120
CO_2 system emission (ton/yr)	0	7.537
CO_2 emission reduction (ton/yr)	2,363	3,583
Balance ($M/yr)	+0.040	+0. 440
Cost for 1 MWh generation ($/MWh)	520	244
Required area of plant (m^2)	60,000	1,280

5.1. Solar PV

Despite the tracking system, a continual increase of utilization in the Korea environment is limited. The most critical factor is the plant cost reduction, which can be effectively achieved by increasing the solar cell efficiency. If solar cells with high efficiency are employed, firstly, the construction and land costs can be substantially reduced. Furthermore, this would increase the power generation and offset the loss due to the annual 3% reduction in incentives. While rooftop or dye-sensitized solar cells may substantially reduce the area of residential systems, the fundamental solution to address the large land requirement of MW-scale plants is increased system efficiency. This can be realized by using novel technologies in the research and demonstration of new systems. These include single-crystal silicon or III-V semiconductor tandem cells (25–40%) and thin-film multi-junction polycrystalline cells (25%), as well as concentrator modules, emerging materials and manufacturing processes.

5.2. MCFC

In contrast to solar PV systems, the currently claimed efficiency of the MCFC is sufficient for positive profit, as shown in Fig. 3.

The economy variation of the system according to the efficiency was estimated and the minimum efficiency required to maintain the breakeven point at the same conditions was calculated as 37.6%, as shown in Fig. 3. Nevertheless, the efficiency will be further increased by operating the system as a combined heat and power (CHP) or gas turbine hybrid, which will improve the economy.

However, the economic success of the MCFC as a commercial system depends on more variables than for the solar PV system. For example, the larger annual O&M cost, which is estimated to be about 37% of the total annual cost. This sensitivity of the MCFC system's utility to the O&M cost means that the cell should be replaced every three years and some parts of BOP need to be operated with steady and careful management. However, these issues will be substantially addressed by future advances in materials and system development.

A more important factor is the system's high susceptibility to the NG price. This is presently the most critical factor influencing the system economy, with 38% of the total paid incentive being consumed to purchase the fuel. The profit variation according to the NG price at the same conditions is shown in Fig. 4.

The limiting NG price to maintain positive profit was estimated to be under 16.28 \$/mmbtu. If the CO_2 penalty cost of NG from Table 2, 4.397 \$/mmbtu, is added to the assumed price, the price rises to 17.39 \$/mmbtu, which exceeds the limiting value. The problem of the NG price is not controlled by the system developer or owner, as in the case of other fossil fuels. Therefore, the future prospect of the MCFC plant is more uncertain than that of the solar system.

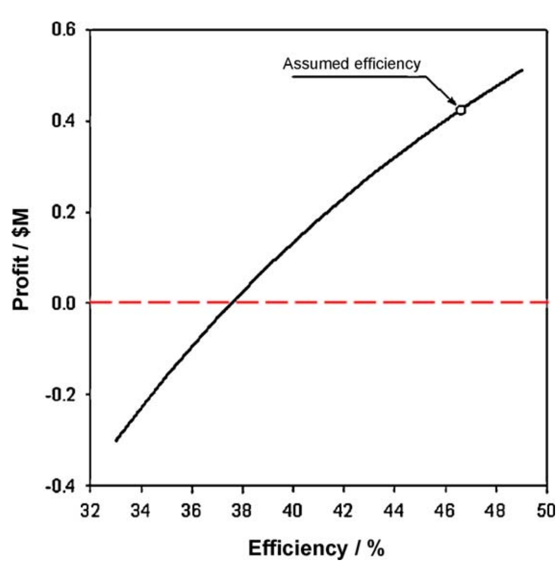

Fig. 3. Economy variation of the MCFC system according to efficiency.

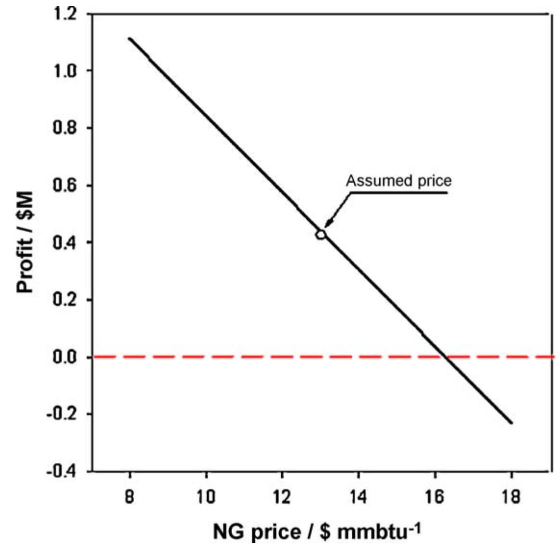

Fig. 4. Economy variation of the MCFC system according to the NG price.

The use of landfill and anaerobic digester gases, as well as biogas, is a potential alternative to NG. Nevertheless, further R&D should be carried out because their CH_4 composition is not constant and their production cost is not yet cheaper than that of NG. Therefore, the high O&M cost and NG price are currently very important issues for the economy of the MCFC system.

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